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(54) Abstract Title

A method of manufacturing a semiconductor laser device

(57) The method comprises growing a cap layer 20 containing a high concentration of crystallographic vacancies over a semiconductor wafer. The wafer is a semiconductor layer structure 14 that contains an active region 17 for laser oscillation. A material 15 for promoting quantum well intermixing, such as SiO_2 is then deposited over selected portions of the wafer. The wafer is annealed to promote quantum well intermixing in selected portions of the active region, and is then cleaved so that the intermixed regions form non-absorbing minor facets of laser devices. The facet regions will have a greater band gap than the rest of the active region, and this will allow a higher power output before catastrophic optical damage occurs.

Growing the cap layer with a high concentration of vacancies improves the efficiency of the intermixing process, and means that the annealing process can be shortened or carried out at a reduced temperature.

A high concentration of vacancies in the cap layer 20 can be obtained by growing the cap layer under non-stoichiometric growth conditions.

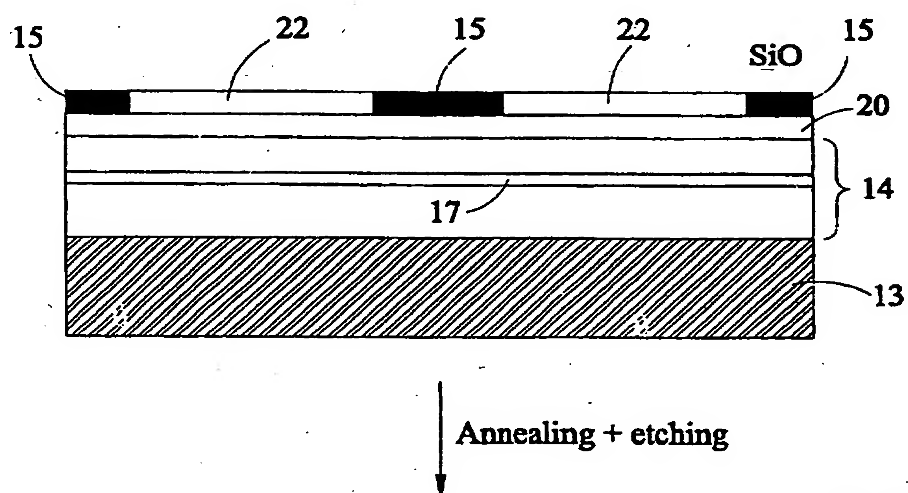

FIG 6(b)

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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

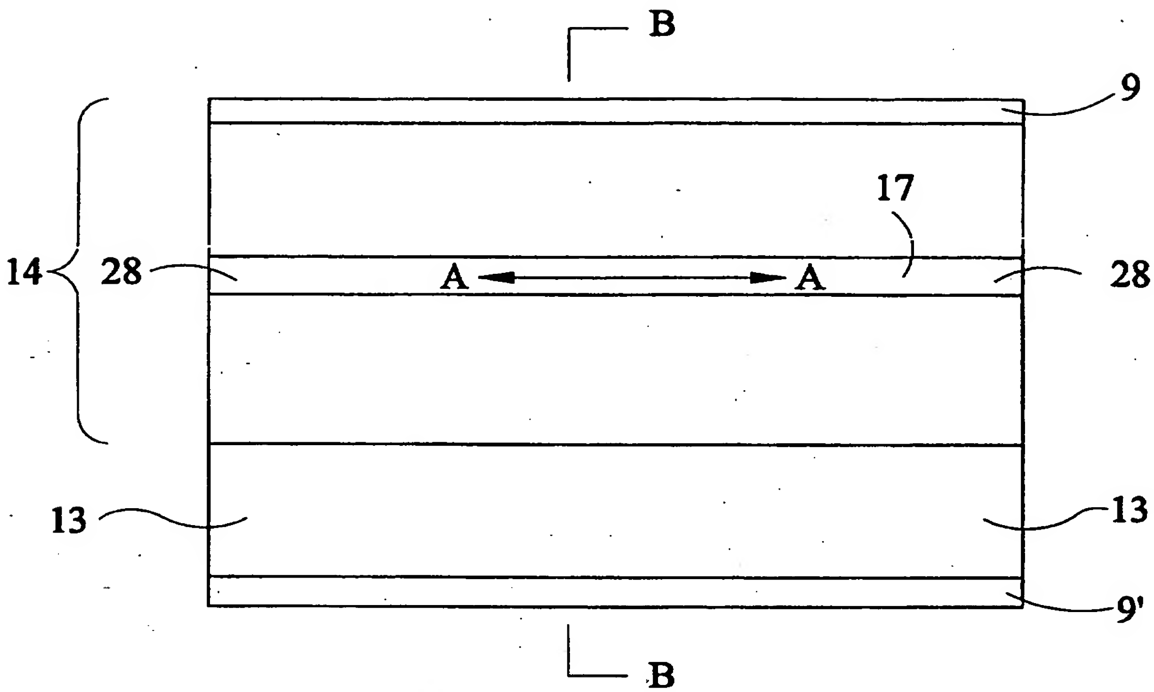


FIG 1(a)

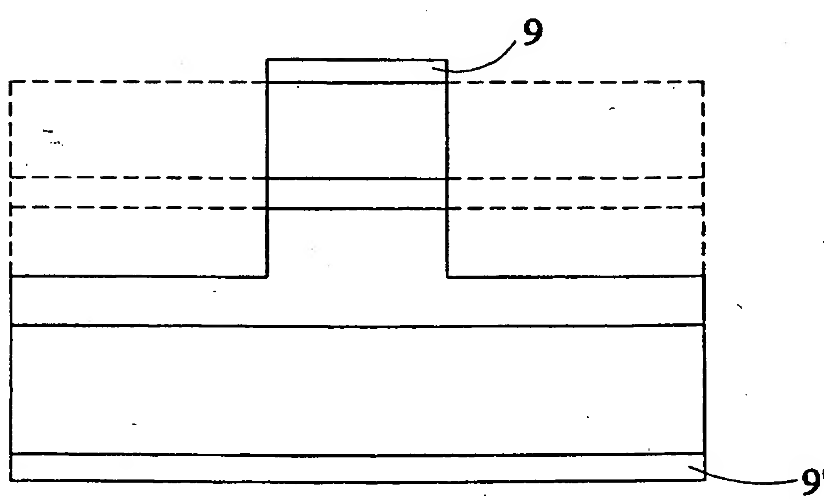


FIG 1(b)

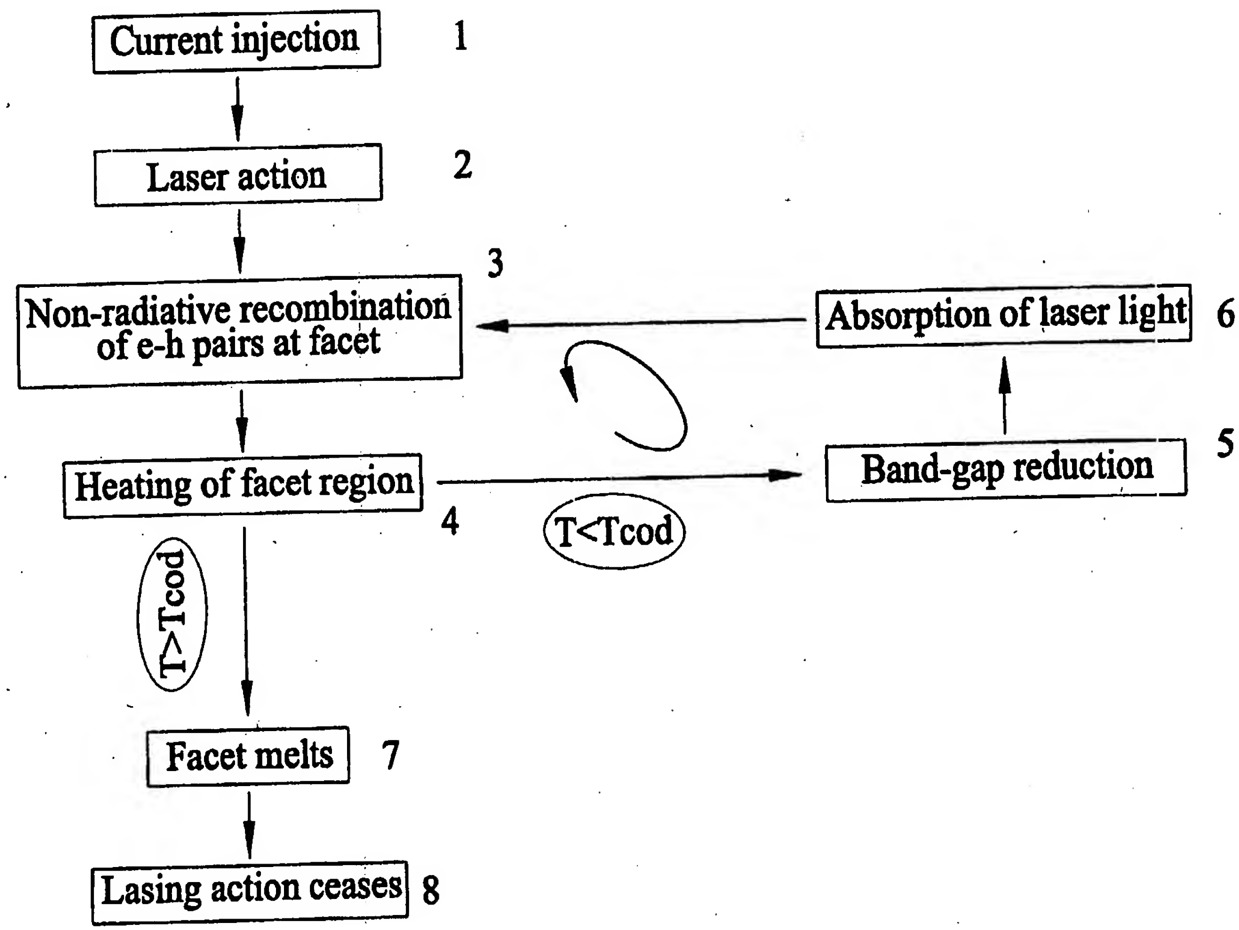

Current injection
1
Laser action
2
Non-radiative recombination of e-h pairs at facet
3
Heating of facet region
4
Band-gap reduction
5
Absorption of laser light
6
T<Tcod
T>Tcod
Facet melts
7
Lasing action ceases
8

FIG 2

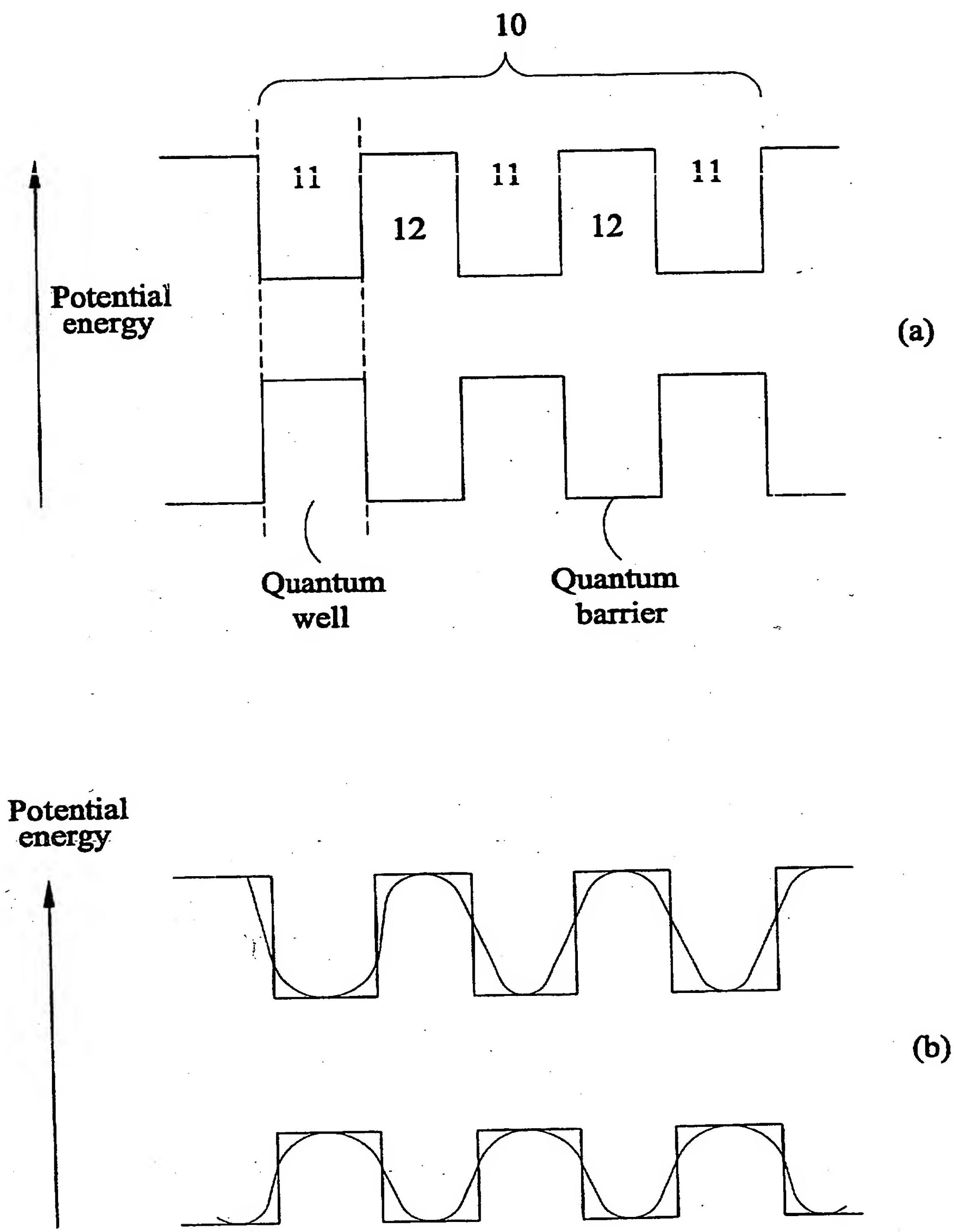

10
11
12
11
12
11
Potential energy
(a)
Quantum well
Quantum barrier
Potential energy
(b)

FIG 3

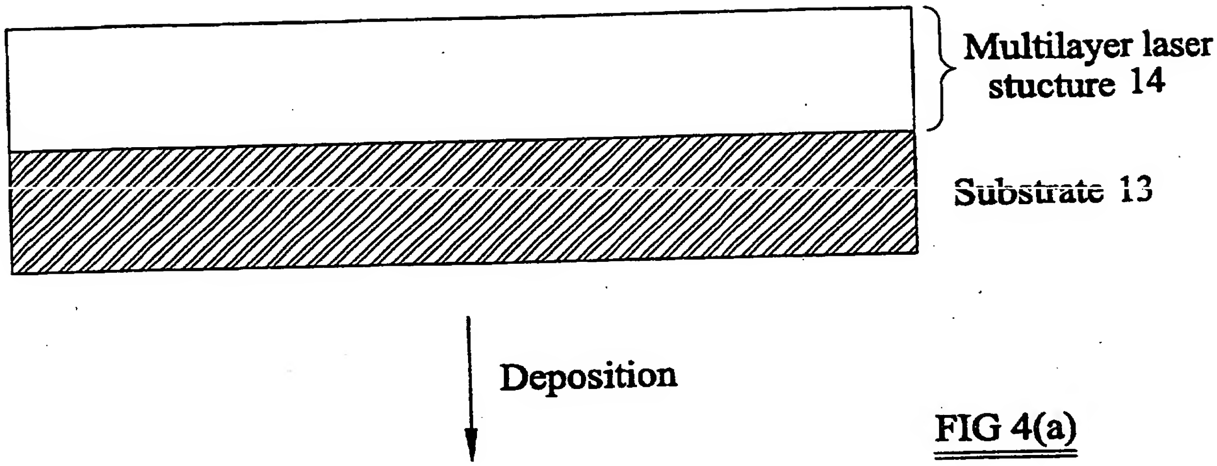


FIG 4(a)

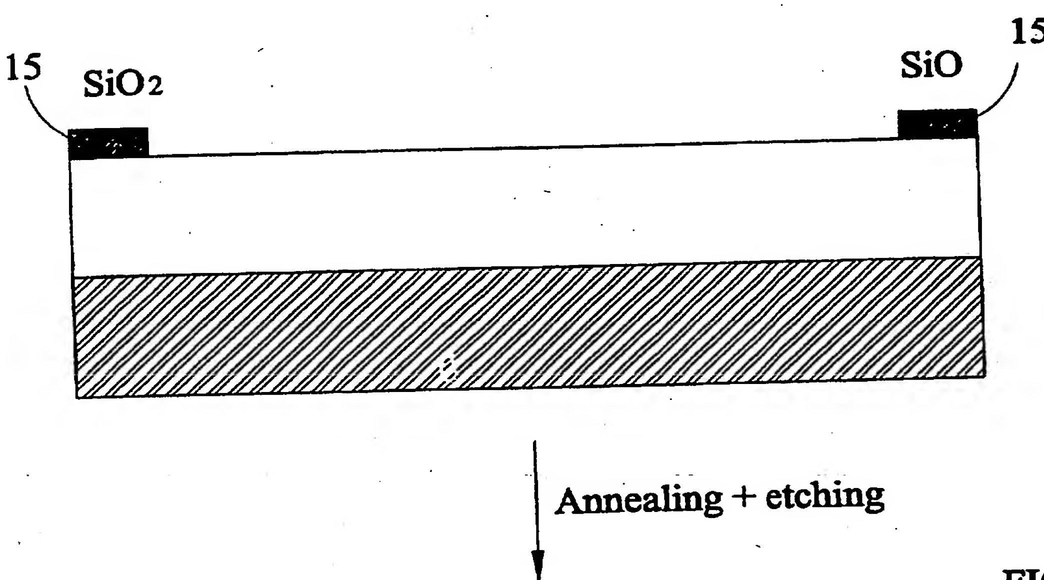


FIG 4(b)

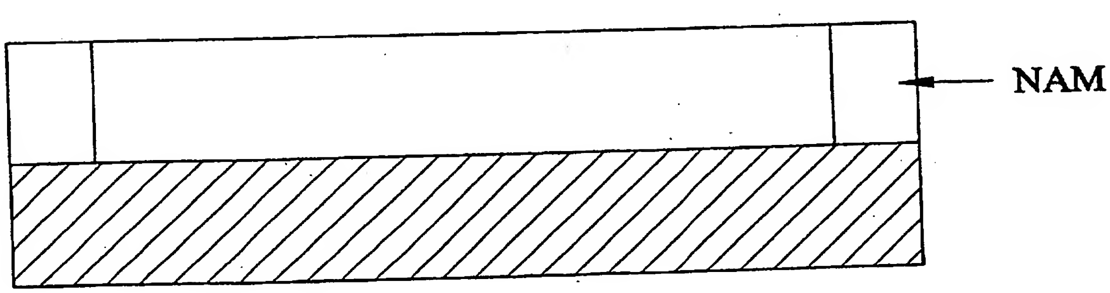


FIG 4(c)

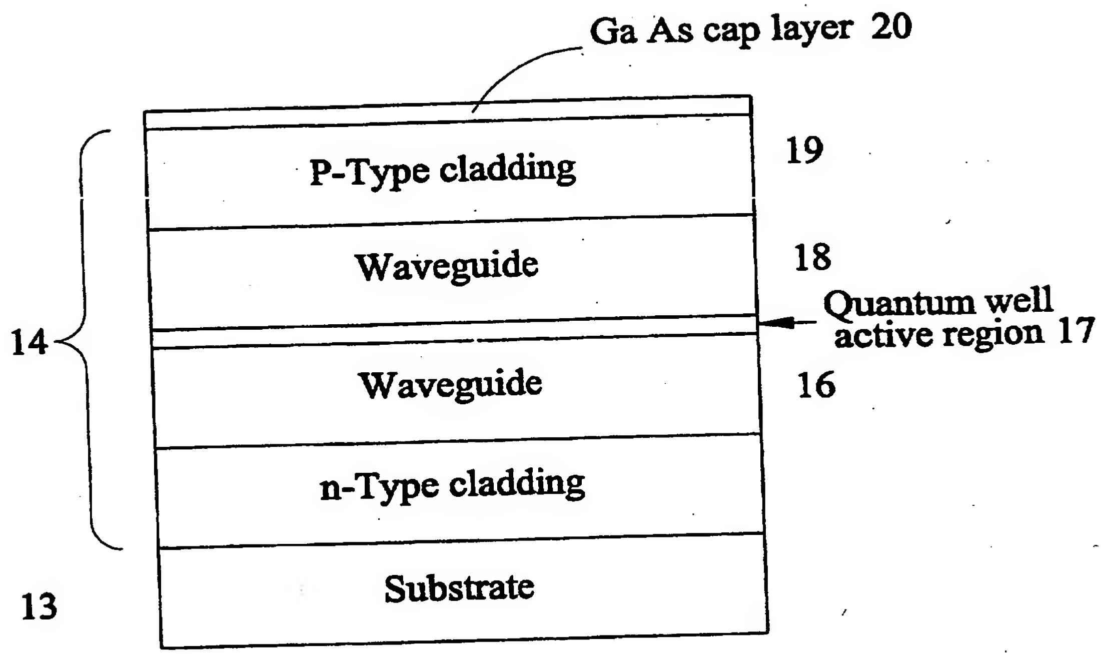

Ga As cap layer 20
P-Type cladding
19
Waveguide
18
Quantum well active region 17
14
Waveguide
16
n-Type cladding
Substrate
13

FIG 5(a)

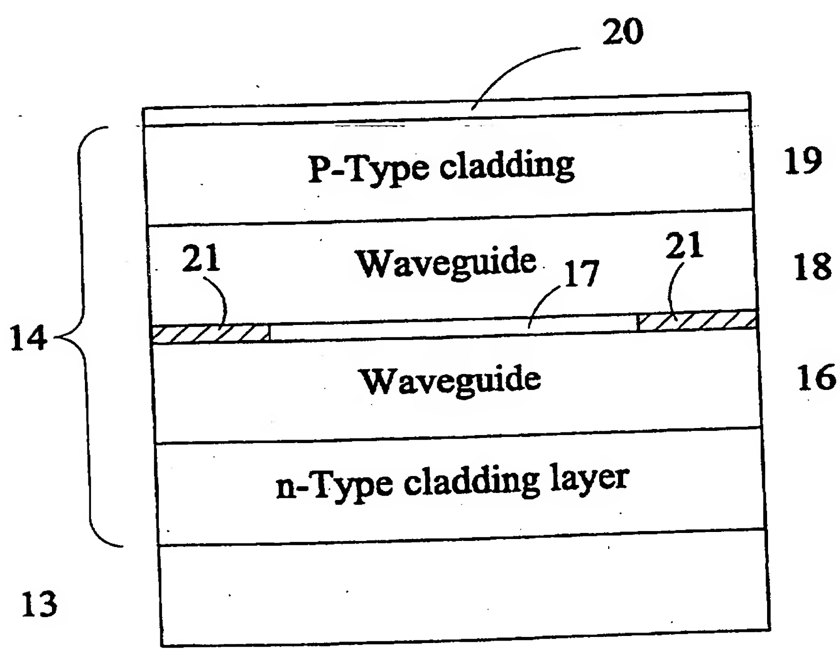
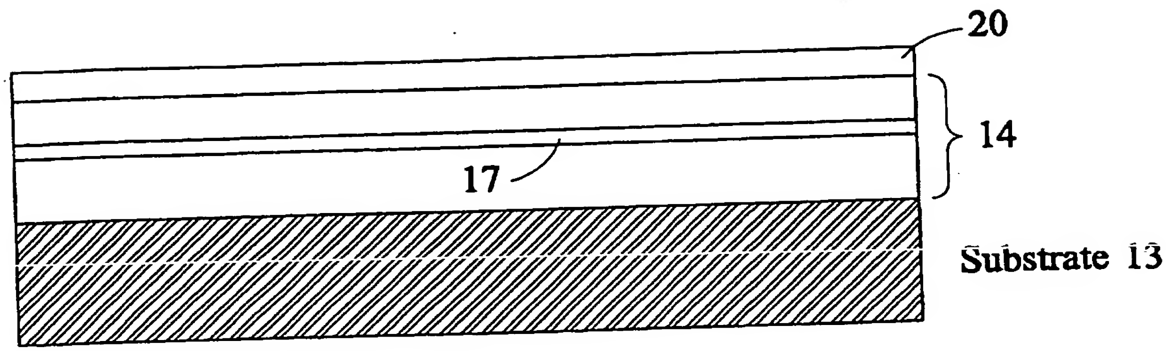
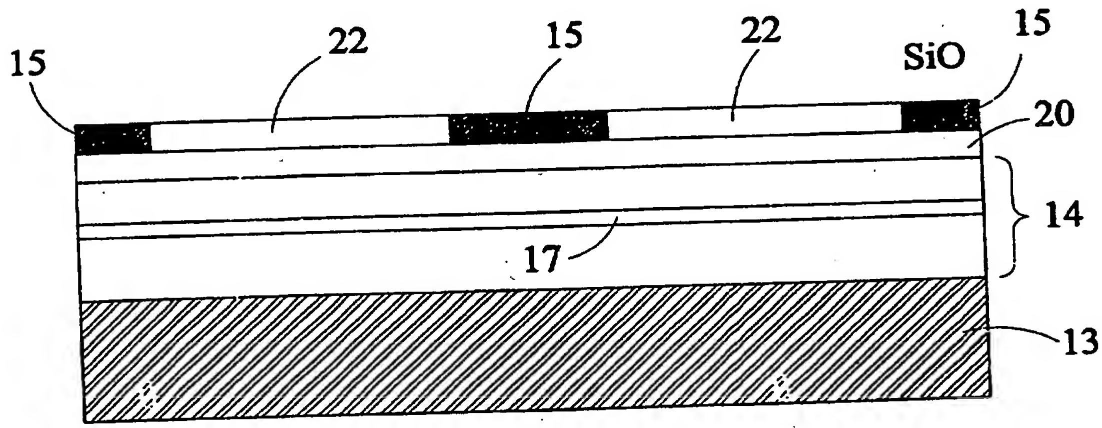

20
P-Type cladding
19
21
Waveguide
17
21
18
14
Waveguide
16
n-Type cladding layer
13

FIG 5(b)



Deposition

FIG 6(a)



Annealing + etching

FIG 6(b)

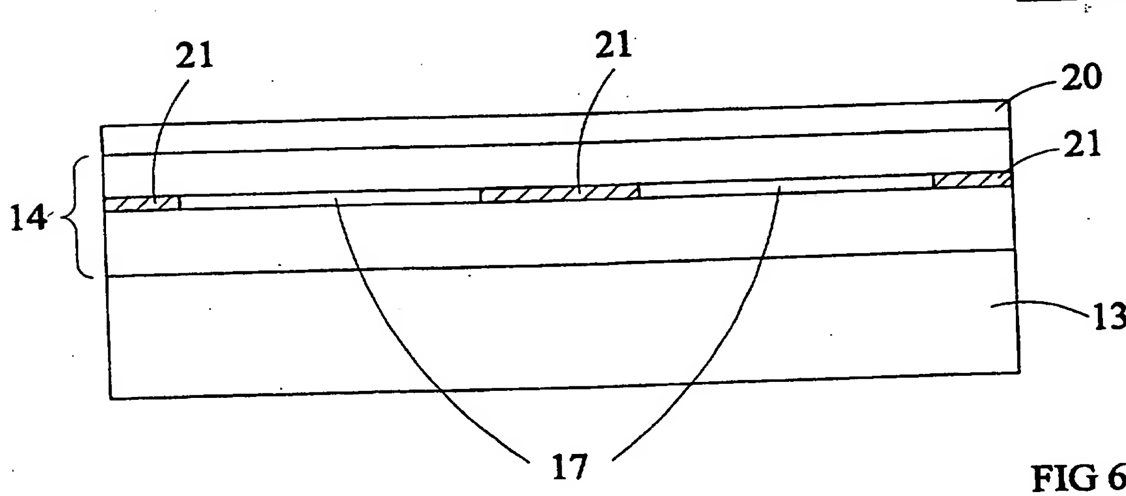


FIG 6(c)

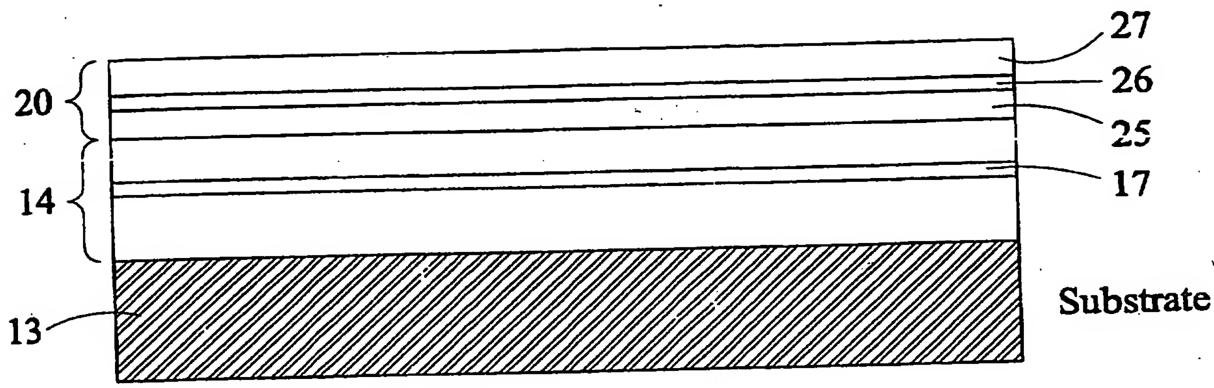

27
26
25
17
20
14
13
Substrate

FIG 7(a)

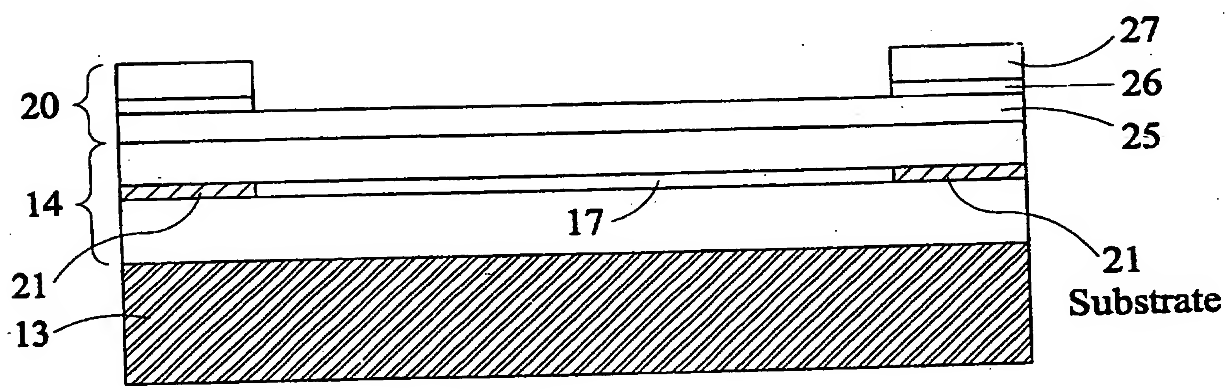

27
26
25
20
14
17
21
21
13
Substrate

FIG 8

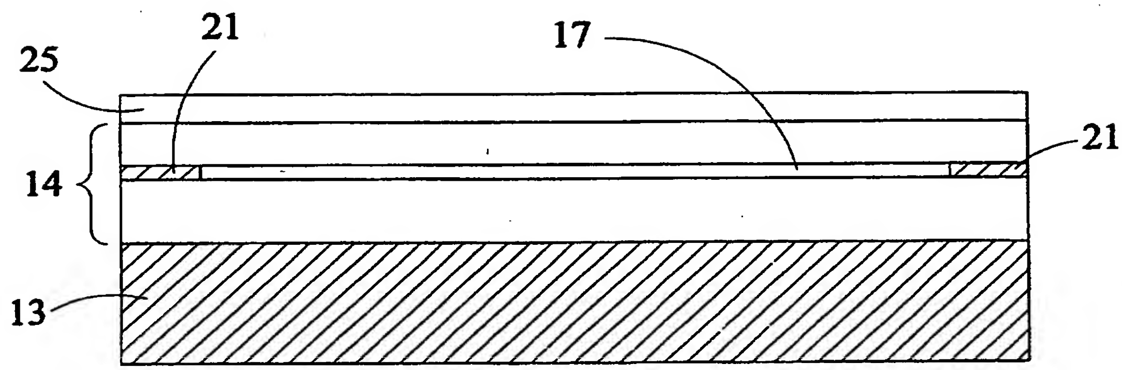


FIG 7(b)

A Method of Manufacturing A Semiconductor Laser Device, and A Semiconductor Laser Device

The present invention relates to a method of manufacturing a semiconductor laser device, and to a semiconductor laser device. In particular, it relates to a method of manufacturing a semiconductor laser device in which the bandgap at a facet is greater than the bandgap of the active region so that heating of the facet is reduced, and to such a semiconductor laser device.

Semiconductor lasers having a high optical output power are in great demand in a variety of applications. For example, in the field of optical storage, use of a light source having a higher optical power enables the read/write time to be reduced, thereby reducing the access time in compact discs, digital video discs, and other magneto-optic storage media. Other applications in which high power output semiconductor lasers are in demand include medical applications, displays, and spectroscopy.

The structure of a semiconductor laser device is shown schematically in Figures 1(a) and 1(b). Figure 1(b) is a cross-section along the line B-B shown in Figure 1(a).

The laser device of Figures 1(a) and 1(b) consists of a semiconductor multilayer structure 14 grown on a substrate 13. The multilayer structure 14 contains an active region 17, which can be, for example, a quantum well layer or a multi-quantum well layer. The device is provided with upper and lower electrodes 9,9' for injecting charge carriers into the active region in order to generate light.

Other layers in the multilayer structure serve to confine light generated in the active region in the direction perpendicular to the substrate, and also to confine carriers within the active layer. In principle the same layers of the multilayer structure can provide both optical confinement and carrier confinement, although often separate layers are provided for each purpose as in the well-known separate confinement heterostructure (SCH) laser in which optical guiding layers are disposed above and below the active

region to provide optical confinement and cladding layers are provided to confine carriers within the active region and the optical guiding layers.

Light is also confined in one direction parallel to the substrate, and this is generally done by arranging for current to be injected only into a stripe-shaped portion of the active region. One way of doing this is to make the upper electrode 9 a stripe electrode as shown in Figure 1(b). It is also possible to remove the parts of the multilayer structure that do not lie under the upper electrode 9, and these parts are shown in broken lines in Figure 1(b). Thus, light generated in the active region 17 is free to propagate in the direction shown by the arrow A-A in Figure 1(a), but is confined in the two directions orthogonal to this propagation direction. The light is effectively propagating within a one-dimensional waveguide.

The end faces 28 of the active region form facets of the laser device. Light propagating within the active region along the direction A-A is substantially reflected at the facets 28; light will thus pass many times through the active region and this generates the optical gain required for laser action to occur. In practice, a semiconductor wafer is grown and is then cleaved to produce many laser devices. The facets are formed during the cleaving process, and may be treated to increase their reflectivity (although it is of course necessary for one facet to be transmissive to some extent to allow light to be emitted from the laser device).

The maximum power output of a semiconductor laser device is limited by a number of factors, but the principal limiting factor is the onset of catastrophic optical damage (COD) to the facets of the laser device. The mechanism by which COD occurs is described by R. Schatz et al in "Journal of Applied Physics" Vol. 76 No. 4, pp2509-2521 (1994). The mechanism is illustrated schematically in Figure 2.

A laser device is operated by injecting current into the active region (step 1), to generate photons as a result of laser action in the active region of the laser device (step 2). The light is emitted from the active region through a facet.

As the power output of the laser device increases, non-radiative recombination of charge carriers will tend to occur in the vicinity of the facet (step 3), and this recombination will cause the generation of heat in the region of the facet (step 4).

If heating of the facet region occurs, this will reduce the bandgap in the vicinity of the facet region (step 5). In a laser where light propagating near a facet region propagates in the same material as the active region, such a decrease in the bandgap of the facet region means that laser light generated in the active region will now be absorbed by the facet region of the laser device (step 6). As a consequence of this absorption of laser light, the rate of carrier generation in the facet region will be increased, thereby increasing the non-radiative recombination of carriers in the facet region, and leading to further generation of heat. It can thus be seen that steps 3, 4, 5 and 6 form a positive feedback loop, which can allow a runaway heating of the facet region to occur. When the temperature of the facet region reaches the threshold temperature for the occurrence of COD (T_{cod}), the facet will suffer damage thereby degrading its optical quality and so degrading the output from the laser device. Moreover, the facet will eventually melt (step 7), at which point the required optical gain will not be generated in the active region so that laser action will cease (step 8).

There are a number of known techniques for increasing the temperature at which COD occurs so as to increase the maximum power output of the laser device. One technique is to treat the facets of the laser device with a chemical passivation technique in order to reduce non-radiative recombination in the facet region. Another known technique is to use a flared waveguide in which the cross-sectional area of the waveguide increases towards the facet region. This reduces the optical power density at the facet, and thus reduces the heat density at the facet thereby delaying the onset of COD.

Another known technique to delay the onset of COD in semiconductor laser devices is to introduce a non-absorbing mirror facet (NAM). This technique is described in U.S. Patent Nos. 5 764 699 and 5 376 582. This technique increases the optical bandgap of the waveguide in the region near the facet. As a result, even if the bandgap in the facet region is reduced as a result of heating of the facet region, the maximum output power

of the laser before the onset of COD is increased. One technique that has been used to increase the bandgap of the waveguide in the region of the facets of the laser is the technique of quantum well inter-mixing.

The active region of a semiconductor laser device typically contains semiconductor quantum wells as shown schematically in Figure 3(a). The upper trace in Figure 3(a) is the conduction band profile of an active region of a laser device, and the lower trace is the valence band profile. It can be seen that the active region 10 consists of a number of quantum wells 11 separated by barrier layers 12. The optical bandgap in the active region, and thus the wave length of light emitted by the active region, is determined by the composition of the quantum well layers 11 and the barrier layers 12, and also by the shape of the conduction band and valence band in the quantum well layers and barrier layers. Normally a quantum well in a laser device has a square well potential profile, as shown in Figure 3(a). However, the technique of inter-mixing mixes the material of the well and the material of the barrier, so that there is no longer an abrupt change in the conduction band and valence band energies at the boundary between a quantum well layer and a barrier layer. Instead, the effect of inter-mixing is to produce a parabolic potential profile as shown in Figure 3(b). Such a parabolic potential profile increases the bandgap of the active region relative to the square well potential profile.

One known technique of obtaining inter-mixing is the impurity-free vacancy disordering method or IFVD. This method is illustrated schematically in Figures 4(a) to 4(c).

Figure 4(a) shows the schematic structure of a semi-conductor laser device. This consists of a multilayer structure 14 disposed on a substrate 13.

The IFVD method of producing a NAM facet is to deposit a layer of SiO_2 on the upper service of the multilayer structure wherever a facet is to be formed. Figure 4(b) shows a layer 15 of SiO_2 deposited over each end of the multilayer structure 14.

The laser structure is then annealed. This causes inter-mixing of the materials in the underlying quantum well active region, but only in the regions under each SiO_2 layer. Finally, the SiO_2 layers are removed by etching, to give the structure shown in Figure 4(c). This is a laser structure in which the active region has a parabolic potential profile in the vicinity of the facets but a square well potential away from the facets, so that the bandgap is greater in the vicinity of the facets than it is away from the facets. Thus, the laser has NAM facets, and the maximum power output of the laser before the onset of COD is increased.

Although the IFVD technique is well-known, its precise physical mechanism is unclear. Several physical processes are known to play an important role.

The IFVD process is applicable to, for example, semiconductor materials that contain gallium. D.G. Deppe has proposed, in "Journal of Applied Physics" Vol. 64, (12) pp R93-R112 (1988), that the high solubility of Ga in SiO_2 at high temperatures leads to an out-diffusion of gallium when an SiO_2 layer is deposited over a gallium-containing semiconductor layer. This leads to the formation of a high concentration of vacancies at Ga sites in the semiconductor layer. If the semiconductor layer is part of a laser multilayer structure, such vacancies created in the semiconductor layer will diffuse towards the quantum well active region of the laser. This diffusion of vacancies towards the active region causes the inter-mixing of the material of the quantum well layers and the material of the barrier layers in the active region, and thus produces the parabolic potential profile shown in Figure 3(b).

P. G. Piva et al have shown, in "Journal of Vacuum Science Technology" B16, (4), pp 1790-1793 (1988), the influence of the concentration of gallium vacancies on the quantum well inter-mixing process. Although they describe inter-mixing using ion-implanted impurities rather than IFVD, the inter-mixing mechanism is thought to be similar.

The IFVD inter-mixing process relies on the formation of vacancies at Ga sites in the semiconductor layer during the steps of depositing the SiO_2 layer and the annealing

step. This is shown by the critical dependence of the mixing process on the method used to deposit the SiO_2 layer and on the subsequent annealing process. The extent of inter-mixing can be determined from the shift in the bandgap of the material, which can be determined by many techniques including, for example, photoluminescence. It has been found that the increase in the bandgap of the material caused by inter-mixing is highly dependent on the process by which the SiO_2 layer is deposited over the semiconductor layer. If the SiO_2 is deposited by sputtering, which is a high-energy deposition process, this is found to be much more effective at promoting inter-mixing than a layer of SiO_2 deposited by a low-energy deposition process such as thermal evaporation or plasma enhanced chemical vapour deposition (PECVD).

The process by which the semiconductor material is annealed has also been found to have a significant effect on the degree of intermixing and thus on the change on the bandgap. Thermal annealing in a furnace has been found to be less effective than rapid thermal annealing (RTA) in which the temperature of the sample is ramped to the annealing temperature in a very short time.

The present invention provides a method of manufacturing a semiconductor laser device comprising the steps of: growing a cap layer over a semiconductor layer structure, the layer structure containing a quantum well active region; depositing a material for promoting quantum well intermixing over a selected part of the cap layer; and annealing the device so as to induce quantum well intermixing in the portion of the active region under the strip of material for promoting quantum well intermixing; wherein the method comprises growing the cap layer under growth conditions that promote the formation of crystallographic vacancies in the cap layer.

By incorporating vacancies in the cap layer during its growth, there is less reliance on out diffusion from the cap layer during the annealing process. The efficiency of the inter-mixing process is increased, and the temperature required during the annealing step is reduced. This is advantageous since high temperature annealing is generally undesirable in a semiconductor device, for example because it can lead to the diffusion

of dopants into the active region of the device and so degrade the performance of the device.

The growth temperature of the cap layer may be selected to promote the formation of crystallographic vacancies in the cap layer. The growth temperature of the cap layer may be lower than the growth temperature of the semiconductor layer structure, or the growth temperature of the cap layer may be higher than the growth temperature of the semiconductor layer structure. Alternatively, the atomic ratio of the material supply of constituents of the cap layer during the growth of the cap layer may be selected to promote the formation of crystallographic vacancies in the cap layer. These are straightforward methods of growing a cap layer that contains an increased concentration of vacancies.

The material for promoting quantum well intermixing may be SiO_2.

The method may further comprise the step of removing the material for promoting quantum well intermixing after the annealing step.

The method may further comprise the step of, before carrying out the annealing step, covering at least one non-selected part of the cap layer with a material that inhibits quantum well intermixing. The material that inhibits quantum well intermixing may be Si_3N_4. The method may further comprise the step of, after the annealing step, removing the material that inhibits quantum well intermixing.

The cap layer may contain Ga, and the crystallographic vacancies may be formed at Ga atomic sites in the cap layer. The cap layer may be a GaAs layer.

Alternatively, the cap layer may be a layer of CdSe, GaP, GaN, InN, AlN, InAs or AlAs.

The cap layer may be grown by molecular beam epitaxy, or by metal - organic chemical vapour deposition.

The step of growing the cap layer may comprise: growing a first cap layer, the growth conditions of the first cap layer being selected such that the first cap layer is substantially stoichiometric; and growing a second cap layer over the first cap layer, the second cap layer being grown under growth conditions that promote the formation of crystallographic vacancies in the second cap layer; and the material for promoting quantum well intermixing may be deposited over one or more selected part(s) of the second cap layer.

The method may further comprise the step of removing the second cap layer after the annealing step. The laser then has a stoichiometric cap layer, and this is preferable if further processing steps are to be carried out on the laser.

Alternatively, the method may further comprise the step of removing only part of the second cap layer after the annealing step. The part(s) of the second cap layer that are left will tend to have a high electrical resistance, and so will block injection of current into the associated parts of the laser.

The method may further comprise the step of growing an etch stop layer between the first cap layer and the second cap layer.

The etch stop layer may be an AlGaAs layer.

A second aspect of the present invention provides a laser device produced by a method as defined above.

A third aspect of the present invention provides a semiconductor layer device comprising: a multilayer structure including an active region for laser oscillation; and a facet; wherein the bandgap of the active region in the vicinity of the facet is greater than the bandgap of the active layer away from the facet; and wherein a non-stoichiometric cap layer is disposed over the multilayer structure.

The non-stoichiometric cap layer may be disposed only over the facet region of the laser.

The laser device may further comprise a stoichiometric cap layer disposed between the non-stoichiometric cap layer and the multilayer structure.

The non-stoichiometric cap layer may contain crystallographic vacancies.

The non-stoichiometric cap layer may contain Ga, and the vacancies may be at Ga atomic sites. The non-stoichiometric cap layer may be a GaAs layer.

Alternatively, the non-stoichiometric cap layer may be a layer of CdSe, GaP, GaN, InN, AlN, InAs or AlAs.

Preferred embodiments of the present invention will now be described by way of illustrative examples with reference to the accompanying figures in which:

Figure 1(a) is a schematic sectional view of a semiconductor laser device;

Figure 1(b) is a cross-section along the line B-B in Figure 1(a);

Figure 2 is a schematic illustration of the mechanism of catastrophic optical damage to a facet of a semiconductor laser device;

Figure 3(a) shows the conduction band and valence band energies of a quantum well active region having a square well potential profile;

Figure 3(b) shows the conduction band and valence band energies of a quantum well active region having a parabolic potential profile;

Figures 4(a) to 4(c) illustrate a known method for the production of a non-absorbing mirror facet;

Figure 5(a) is a schematic cross-sectional view of a semiconductor wafer;

Figure 5(b) is schematic cross-sectional view of a semiconductor laser device according to a first embodiment of the present invention;

Figures 6(a) to 6(c) illustrate a method of producing a laser device according to the first embodiment of the invention;

Figure 7(a) is schematic cross-sectional view of another semiconductor wafer;

Figure 7(b) is schematic cross-sectional view of a semiconductor laser device according to a second embodiment of the present invention; and

Figure 8 is schematic cross-sectional view of a semiconductor laser device according to a third embodiment of the present invention.

Figure 5(a) shows a semiconductor wafer that is used to produce a semiconductor laser device according to a first embodiment of the present invention. This wafer comprises a multilayer structure 14 grown on a substrate 13. The multilayer structure shown in Figure 5(a) consists of an n-type cladding layer, a first waveguiding layer 16, a quantum well active region 17, another waveguiding region 18, and a p-type cladding region 19. However, the invention is not limited to this particular multilayer structure but can be used with any conventional semiconductor laser structure. The multilayer structure 14 can be grown by any standard epitaxial grown technique such as, for example, molecular beam epitaxy or metal organic chemical vapour deposition (MOCVD).

In the first embodiment of the present invention, a cap layer 20 containing Ga is grown on the multilayer structure 14. In the embodiment of Figure 5 the cap layer is a layer of GaAs. According to the invention, the cap layer is grown so it incorporates vacancies at Ga sites. This can be achieved by growing the cap layer 20 under different growth conditions than the growth conditions used for the rest of the multilayer structure 14.

Providing a cap layer that incorporates vacancies at Ga sites promotes inter-mixing when an IFVD process is carried out.

A method of producing a laser device according to the invention is illustrated in Figures 6(a) to 6(c).

In the first step, the multilayer laser structure 14 is grown on a substrate 13 by any standard epitaxial growth process. Of the individual layers in the multilayer structure, only the active layer 17 is shown in Figures 6(a) to 6(c), for clarity. A GaAs cap layer 20 is then deposited over the multilayer structure 14. According to the invention, the cap layer 20 is deposited under growth conditions that induce the formation of a large density of vacancies at Ga sites in the cap layer 20.

The stoichiometric growth of GaAs in general produces a very low concentration of vacancies in the material. Where a GaAs layer is grown by MBE, stoichiometric growth is normally obtained at a growth temperature in a range of 350-730° C and a V/III flux ratio of 1:1 (see, for example, J.Y. Tsao, "Materials Fundamentals of Molecular Beam Epitaxy" pp 65-88, Academic Press (1993)). These figures are, however, sensitive to the exact growth condition and, moreover, different growth techniques such as MOCVD require different growth conditions to obtain stoichiometric growth.

A layer of GaAs which contains a high concentration of vacancies at Ga sites may be obtained through the non-stoichiometric growth of GaAs. One way of obtaining non-stoichiometric growth of GaAs is to perform the growth at a temperature below the temperature range required for stoichiometric growth. For an MBE growth process, a growth temperature in the range of around 200-350°C will produce non-stoichiometric growth of GaAs, and will thus lead to a GaAs layer having a large concentration of vacancies of Ga sites. Growth at a temperature below the temperature range required to give stoichiometric growth will hereinafter be referred to as "low temperature growth".

Non-stoichiometric growth can also be obtained by performing the growth process at a temperature greater than the temperature range at which stoichiometric growth occurs. In the case of MBE growth, for example, growth at a temperature range of 730°C or above will produce a GaAs layer having a high concentration of vacancies at Ga sites. Growth at a temperature greater than the temperature range that provides stoichiometric growth will be referred to hereinafter as "high temperature growth".

It is also possible to obtain non-stoichiometric growth by varying the V/III flux ratio. A V/III flux ratio of < 1 will typically produce a GaAs layer that is rich in Ga, and contains Ga atoms at interstitial sites and vacancies at arsenic sites. A V/III ratio of > 1 will tend to produce a GaAs layer that is rich in As, and contains vacancies at Ga sites and As atoms at interstitial sites. The exact effect of varying the V/III ratio is dependent however on a number of other parameters of the growth process.

Figure 6 (a) shows the multilayer structure 14 after the cap layer 20 containing vacancies at Ga lattice sites has been grown.

The next step is to deposit a material that promotes intermixing on selected areas of the wafer. In this embodiment, SiO_2 (silicon dioxide) is used as the layer to promote intermixing. Silicon dioxide is deposited on selected areas of the epitaxial wafer where it is desired to promote intermixing. These areas are defined by any standard lithographic process. Typically, the silicon dioxide will be deposited in stripes over the wafer to define the facet areas of the individual laser bars that will be obtained once the wafer has been cleaved. The silicon dioxide stripes are typically 10-200 μm wide, so that once the wafer is cleaved this leads to NAM regions next to the facets having a width in the region 5-100 μm. The precise width of the NAM region that is required will be determined by the exact dependence on the onset of COD on the width of the NAM region.

For clarity, Figure 6(b) shows only three strips of silicon dioxide 15a,15b,15c deposited on the cap layer 20. The wafer will be cleaved down the centre of the central strip of silicon dioxide 15b, whereas the wafer will not be cleaved along the two outer strips of

silicon dioxide 15a,15c; the two outer strips of silicon dioxide 15a,15c are therefore approximately half the width of the central strip of silicon dioxide 15b. In practice, however, there would be a large number of strips of silicon dioxide deposited on a single wafer since a wafer is cleaved to produce a large number of laser devices..

It is preferable that the silicon dioxide strips 15a,15b,15c are deposited by a high energy deposition process, since this will tend to induce further vacancies at Ga lattice sites in the cap layer 20 and possibly in the upper part of the multilayer structure 14 (the greater the energy of the deposition process, the greater the depth at which vacancies will be induced). However, since the cap layer 20 already contains intrinsic vacancies at Ga sites it is possible to use other growth processes to deposit the cap silicon dioxide strips, for example a low energy deposition process such as thermal evaporation or PECVD.

Once the silicon dioxide strips 15a,15b,15c have been deposited on the cap layer, the wafer is annealed to induce quantum well intermixing in the regions of the active layer under the silicon dioxide strips 15a,15b,15c. This can be done using a standard annealing process, for example a RTA process as discussed above with regard to the known method of Figures 4(a) to 4(c). However, according to the present invention, the cap layer 20 containing a high concentration of vacancies at Ga sites enhances the intermixing process, so that the parameters of the annealing process are less stringent in the present application than in the prior art IFVD process. For example, simple furnace annealing without rapid temperature ramping can be used. Alternatively, the temperature and/or duration of the annealing process can be reduced, so that the risk that dopants in the multilayer structure will diffuse into the active region is reduced.

Once the annealing process has been carried out, the silicon dioxide strips 15 are removed using, for example, a standard hydrogen fluoride etching technique. As shown in Figure 6(c), this will leave a wafer having a multilayer laser structure in which the active layer 17 contains regions 21 having an increased bandgap. These regions of increased bandgap are at positions corresponding to the positions of the strips 15a,15b,15c of silicon dioxide.

Figure 5(b) shows the structure of a laser obtained by cleaving the wafer shown in Figure 6(c). The increased bandgap regions 21 will act as NAM facets, and the maximum power output of the laser before the onset of COD will be increased.

Once the silicon dioxide strips 15a,15b,15c have been removed, the wafer can be processed in a conventional manner. For instance, the wafer may be etched to produce ridge laser structures, and metallic contacts to the n-type cladding layer and p-cladding layer can be provided. Such processing steps would generally be carried out before the wafer is cleaved into individual laser bars.

The parts of the wafer that are not covered by the strips of material to promote quantum well intermixing are preferably covered by a material that acts as a barrier to intermixing. These layers are shown as 22 in Figure 6(b). A suitable material for the strips 22 is Si_3N_4. This material can be conveniently deposited by PECVD. The strips 22 of Si_3N_4 are also removed during the etching step to remove the silicon dioxide layers 15a,15b,15c. In principle, however, the strips 22 can be omitted, so that only the silicon dioxide strips 15a,15b,15c are deposited on the surface of the semi-conductor wafer.

Figure 7(a) illustrates another semiconductor wafer. This wafer can be used to obtain a laser device according to another embodiment of the invention. As with the wafer used in the method shown in Figure 6(a) to 6(c), this wafer comprises a substrate 13, a semi-conductor multilayer structure 14 that includes a quantum well active layer 17, and a cap layer 20. The other layers of the multilayer structure are not included in Figure 7(a) for ease of illustration.

In the wafer of Figure 7(a), the cap layer 20 is formed of three separate layers. Initially a GaAs layer 23 is grown on the multilayer structure 14 under stoichiometric growth conditions. An etching stop layer 26 is then grown over the first cap layer 25. This can be, for example, a thin AlGaAs layer. The etching stop layer 26 is preferably grown under stoichiometric growth conditions. Finally, a second cap layer 27 that contains Ga, such as, for example, a GaAs layer, is grown over the etching stop layer 26. This is

grown under non-stoichiometric growth conditions, and so incorporates a high concentration of vacancies at Ga sites.

The wafer shown in Figure 7(a) is processed in the manner described above with reference to Figures 6(a) to 6(c) up to and including the etching step of removing the silicon dioxide strips by etching with hydrogen fluoride solution. Once the hydrogen fluoride etching step has been completed, the non-stoichiometric GaAs layer 27 is then removed by an etching process chosen so as to have no etching effect on the etch stop layer 26. The etching process used to remove the second cap layer 27 can be any suitable standard etching process, for example etching using $NH_3OH:H_2O_2$.

Once the second cap layer 27 has been removed, the etching stop layer is then removed by a selective etching process which does not affect the underlying first cap layer 25. A suitable etching process for removing the etching stop layer 26 is etching with hydrogen fluoride.

Figure 7(b) shows a laser produced from the wafer of Figure 7(a). This laser is generally similar to the laser of Figure 5(b), except that the laser structure of Figure 7(b) is capped by a stoichiometric GaAs cap layer rather than by a non-stoichiometric layer as in the embodiment of Figure 5(b). This is more advantageous for further processing of the laser structure.

The processes of depositing an SiO_2 layer and annealing the wafer can cause damage to the cap layer, and this damage can make it difficult to deposit ohmic contacts on the wafer. In this embodiment of the present invention, however, any damage will occur primarily in the second cap layer 27, which is removed before the step of depositing contacts is carried out. The contacts will be deposited on the first cap layer 25, and this will in general be substantially free of damage. It is therefore easier to deposit good quality contacts on the laser of Figure 7(b) than a on laser structure in which the non-stoichiometric cap layer is not removed.

A further advantage of removing the non-stoichiometric cap layer is that it is known that a non-stoichiometric cap layer that has been annealed can become electrically resistive, as explained below. The presence of an electrically resistive layer in the laser structure is undesirable, since it will again make it difficult to deposit ohmic contacts on the laser device.

In a further embodiment, the step of etching the second cap layer 27 described with regard to Figures 7(a) and 7(b) above is performed only in the areas of the wafer away from the regions in which intermixing has occurred. In this embodiment, when the wafer is cleaved to form laser bars, a portion of the second capping layer 27 will remain over the NAM facet regions of the laser. A laser according to this embodiment of the invention is shown schematically in Figure 8.

It is known that the process of annealing a non-stoichiometric GaAs layer, and in particular a non-stoichiometric GaAs layer that contains As atoms at interstitial sites, can result in the layer becoming electrically resistive owing to the formation of precipitates of arsenic. If the non-stoichiometric GaAs layer is left in place over the NAM facet regions of the laser device, these resistive layers will inhibit the flow of current into the facet regions, and this will reduce the amount of non-radiative recombination of carriers that occurs in the facet regions and thereby further increase the maximum output power before COD occurs.

The present invention has been described above with reference to lasers in which the cap layer is a layer containing Ga, such as a layer of GaAs. The present invention is not, however, limited to a cap layer that contains Ga, but can be applied to other semiconductor materials. Other materials for the cap layer to which the invention can be applied include, but are not limited to, CdSe, GaP, GaN, InN, AlN, InAs and AlAs.

In the embodiments described above silicon dioxide (SiO_2) is used as the material for promoting intermixing on selected areas of the wafer. The invention is not, however, limited to the use of SiO_2, and different materials may be applicable for different semiconductor systems.

CLAIMS:

1. A method of manufacturing a semiconductor laser device comprising the steps of:

growing a cap layer over a semiconductor layer structure, the layer structure containing a quantum well active region;

depositing a material for promoting quantum well intermixing over a selected part of the cap layer; and

annealing the device so as to induce quantum well intermixing in the portion of the active region under the strip of material for promoting quantum well intermixing;

wherein the method comprises growing the cap layer under growth conditions that promote the formation of crystallographic vacancies in the cap layer.

2. A method as claimed in claim 1 wherein the growth temperature of the cap layer is selected to promote the formation of crystallographic vacancies in the cap layer.

3. A method as claimed in claim 2 wherein the growth temperature of the cap layer is lower than the growth temperature of the semiconductor layer structure.

4. A method as claimed in claim 2 wherein the growth temperature of the cap layer is higher than the growth temperature of the semiconductor layer structure.

5. A method as claimed in claim 1 wherein the atomic ratio of the material supply of constituents of the cap layer during the growth of the cap layer is selected to promote the formation of crystallographic vacancies in the cap layer.

6. A method as claimed in any preceding claim wherein the material for promoting quantum well intermixing is SiO_2.

7. A method as claimed in any preceding claim and further comprising the step of removing the material for promoting quantum well intermixing after the annealing step.

8. A method as claimed in any preceding claim and further comprising the step of, before carrying out the annealing step, covering at least one non-selected part of the cap layer with a material that inhibits quantum well intermixing.

9. A method as claimed in claim 8 wherein the material that inhibits quantum well intermixing is Si_3N_4.

10. A method as claimed in claim 8 or 9 and further comprising the step of, after the annealing step, removing the material that inhibits quantum well intermixing.

11. A method as claimed in any preceding claim wherein the cap layer contains Ga, and the crystallographic vacancies are formed at Ga atomic sites in the cap layer.

12. A method as claimed in claim 11 wherein the cap layer is a GaAs layer.

13. A method as claimed in any of claims 1 to 10 wherein the cap layer is a layer of CdSe, GaP, GaN, InN, AlN, InAs or AlAs.

14. A method as claimed in any preceding claim wherein the cap layer is grown by molecular beam epitaxy.

15. A method as claimed in any of claims 1 to 13 wherein the cap layer is grown by metal-organic chemical vapour deposition.

16. A method as claimed in any preceding claim wherein the step of growing the cap layer comprises:

growing a first cap layer, the growth conditions of the first cap layer being selected such that the first cap layer is substantially stoichiometric; and

growing a second cap layer over the first cap layer, the second cap layer being grown under growth conditions that promote the formation of crystallographic vacancies in the second cap layer;

and wherein the material for promoting quantum well intermixing is deposited over one or more selected part(s) of the second cap layer.

17. A method as claimed in claim 16 and further comprising the step of removing the second cap layer after the annealing step.

18. A method as claimed in claim 16 and further comprising the step of removing only part of the second cap layer after the annealing step.

19. A method as claimed in claim 16, 17 or 18 and further comprising the step of growing an etch stop layer between the first cap layer and the second cap layer.

20. A method as claimed in claim 19 wherein the etch stop layer is an AlGaAs layer.

21. A method substantially as described herein with reference to Figures 6(a) to 6(c) of the accompanying drawings.

22. A laser device produced by a method as defined in any of claims 1 to 21.

23. A semiconductor laser device comprising: a multilayer structure including an active region for laser oscillation; and a facet;

wherein the bandgap of the active region in the vicinity of the facet is greater than the bandgap of the active layer away from the facet;

and wherein a non-stoichiometric cap layer is disposed over the multilayer structure.

24. A semiconductor laser device as claimed in claim 23 wherein the non-stoichiometric cap layer is disposed only over the facet region of the laser.

25. A semiconductor laser device as claimed in claim 23 or 24 and further comprising a stoichiometric cap layer disposed between the non-stoichiometric cap layer and the multilayer structure.

26. A laser device as claimed in any of claims 23 to 25 wherein the non-stoichiometric cap layer contains crystallographic vacancies.

27. A laser device as claimed in any of claims 23 to 26 wherein the wherein the non-stoichiometric cap layer contains Ga, and wherein the vacancies are at Ga atomic sites.

28. A laser device as claimed in claim 27 wherein the non-stoichiometric cap layer is a GaAs layer.

29. A laser device as claimed in any of claims 23 to 26 wherein the non-stoichiometric cap layer is a layer of CdSe, GaP, GaN, InN, AlN, InAs or AlAs.

30. A laser device substantially as described herein with reference to Figure 5(b) of the accompany drawings or to Figure 7(b) of the accompany drawings or to Figure 8 of the accompany drawings

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Application No: GB 0000519.9

Claims searched: All

Examiner: COLIN STONE

Date of search: 19 April 2000

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.R): H1K(KELF,KELQ,KELX)

Int Cl (Ed.7): H01L

Other: ON LINE,W.P.I.,EPODOC,JAPIO

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X	US 5764669	MITSUBISHI DENKI (See cap layer 4a and facets 3b,Fig.5b)	23
X	US 5708674	XEROX (See cap layer 31,Fig.7)	23
X	US 5376582	I.B.M. (See cap layer 24,Fig.7)	23

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